

A 22° Tidal Tail for Palomar 5

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ABSTRACT

Using Data Release 4 of the Sloan Digital Sky Survey, we have applied an optimal contrast, matched filter technique to trace the trailing tidal tail of the globular cluster Palomar 5 to a distance of 18.5 degrees from the center of the cluster. This more than doubles the total known length of the tail to some 22 degrees on the sky. Based on a simple model of the Galaxy, we find that the stream's orientation on the sky is consistent at the 1.7σ level with existing proper motion measurements. We find that a spherical Galactic halo is adequate to model the stream over its currently known length, and we are able to place new constraints on the current space motion of the cluster.

Subject headings: globular clusters: general — globular clusters: individual(Palomar 5) — Galaxy: Structure — Galaxy: Halo

1. Introduction

The tidal tails of globular clusters are very interesting from a dynamical standpoint as they are expected to be very cold (Combes, Leon, & Meylan 1999). This should make them

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useful for constraining not only the orbits of the clusters themselves, but for probing both the global mass distribution of the Galaxy and its lumpiness (Murali & Dubinski 1999). Tidal tails in globular clusters were first discovered in photographic surveys (Grillmair et al. (1995); Leon, Meylan, & Combes (2000)) and now number over 30 in both the Galaxy and in M 31 (Grillmair et al. 1996). Most recently, Grillmair & Johnson (2006) detected a tidal stream associated with NGC 5466 which subtends some 45° on the sky.

Among the first discoveries in the Sloan Digital Sky Survey (SDSS) data were the remarkably strong tidal tails of Palomar 5 (Odenkirchen et al. 2001; Rockosi et al. 2002; Odenkirchen et al. 2003), spanning over 10° on the sky. Grillmair & Smith (2001) found evidence for a stellar mass function relatively depleted of lower mass stars, and Koch et al. (2004) found that these lower mass stars have indeed made their way into Pal 5’s tidal stream. Pal 5 may well be on its last orbit around the Galaxy before dissolving completely.

In this paper we examine Data Release 4 of the SDSS, which encompasses an area not available to Odenkirchen et al. (2003). We briefly describe our analysis in Section 2. We discuss our findings in Section 3, and make concluding remarks in Section 4.

2. Data Analysis

Data comprising u' , g' , r' , i' , and z' photometric measurements and their errors for 3.7×10^6 stars in the region $224^\circ < \text{R.A.} < 247^\circ$ and $-3^\circ < \delta < +10^\circ$ were extracted from the SDSS DR4 database using the SDSS CasJobs query system. The data were analyzed using the matched-filter technique described by Rockosi et al. (2002), and the reader is referred to this paper for a complete description of the method. Briefly, we constructed an observed color-magnitude density or Hess diagram for Pal 5 using stars within $5'$ of the cluster center. An optimum star count weighting function was created by dividing this color-magnitude distribution function by a similarly binned color-magnitude distribution of the field stars. The Hess diagram for field stars was created using several regions to the east and west of Pal 5 and the stream, together subtending ~ 147 square degrees. The resulting weighting function was then applied to all stars in the field and the weighted star counts were summed by location in a two dimensional array.

We used all stars with $16 < g' < 22$, dereddened as a function of position on the sky using the DIRBE/IRAS dust maps of Schlegel, Finkbeiner, & Davis (1998). The distribution of $E(B - V)$ across the field is shown in Figure 1 and ranges from 0.02 along the northern edge of the field to 0.35 along the southern edge.

We optimally filtered the $g' - u'$, $g' - r'$, $g' - i'$, and $g' - z'$ star counts independently and

then co-added the resulting weight images. As expected, most of the filter weight is given to main sequence turn-off and horizontal branch stars, as these populations lie blueward of the vast majority of field stars. In Figure 2 we show the co-added, filtered star count distribution for stars on the giant branch and the main sequence. The image has been smoothed with a Gaussian kernel of width $\sigma = 0.15^\circ$. A low-order, polynomial surface was fitted and subtracted from the image to remove large scale gradients due to the Galactic disk and bulge. The blank area running eastward from just north of Pal 5 and the several blank areas on the eastern end of the field are regions not included in the SDSS DR4. We note that the region just north of the cluster (containing the globular cluster M 5) *is* included in the dataset considered by Odenkirchen et al. (2003), and the reader is referred to this work for a glimpse of Pal 5’s trailing tail in the region $1.3^\circ < r < 3.2^\circ$ from the cluster.

3. Discussion

Figure 2 clearly shows a long stream of stars with Pal 5’s color-luminosity distribution, extending from R.A., dec = $(226.3^\circ, -2.9^\circ)$ to $(246^\circ, +7.9^\circ)$. The southern, leading tail has already been described in detail by Odenkirchen et al. (2003), as has the portion of the northern tail westward of R.A. = 234° . The new result here is the additional 12° of trailing tidal tail extending to R.A. = 246° . The feature is quite strong, and appears as a continuous extension of the trailing tail identified by Odenkirchen et al. (2003). The feature vanishes if the weighting filter is shifted 0.5 magnitudes blueward or redward of the Pal 5’s observed main sequence.

Comparing Figures 1 and 2, there are clear correlations between regions of high color excess and areas of reduced star count density. (e.g. 2° SE of the cluster, and at R.A., dec = $239^\circ, 3.3^\circ$). This is to be expected, given that SDSS sample completeness will be a function of apparent magnitude. The distribution of foreground dust will affect both the apparent shape and the number counts along Pal 5’s tidal tails. The effect of the dust can be reduced by counting only the brighter stars, but at some considerable cost to signal to noise ratio. This is particularly true at the eastern end of the tail, where contamination by foreground bulge stars is almost twice what it is in the vicinity of the cluster itself.

To investigate whether the additional arc of Pal 5’s tail could be due to confusion with background galaxies we have reanalyzed the same survey area using as input those objects classified in DR4 as galaxies. We find no indication of significant enhancements in the galaxy counts, either extended along the feature, or as discrete components of it. We conclude that star-galaxy confusion cannot be held to account for the extended northern feature.

For all these reasons, we conclude that the feature extending from R.A., dec = $(234^\circ, 3.2^\circ)$ to $(246^\circ, 7.9^\circ)$ is a *bona fide* portion of Pal 5’s trailing tidal tail. As found by Odenkirchen et al. (2003) for the inner portion of the tails, the linear density of stars continues to fluctuate along the extended tail, rising to more than 200 stars per linear degree at R.A. $\approx 240.6^\circ$, and dropping almost to undetectability at R.A. $\approx 236.8^\circ$ and 242.8° . We do not expect significant diminution in the filter output due to changes in the average distance between the Sun and the stream. Based on the best-fit orbit model described below, the distance between us and the stream increases from 23.2 kpc at the cluster itself to 23.9 kpc at apogalacticon (which occurs at R.A. $\approx 235^\circ$), dropping back down to 23.2 kpc at R.A. = 246° . Given the photometric uncertainties, this variation in distance modulus (0.06 mag) is too small to have any noticeable effect on the output of a matched filter which is optimized for stars at the distance of Pal 5. The density fluctuations along the stream must therefore be real and are presumably a natural consequence of the episodic nature of tidal stripping of a cluster on an eccentric and disk-crossing orbit.

In Figure 3 we show the distribution of 78 candidate blue horizontal branch stars. There is no obvious tendency for these stars to be distributed along the tidal tails - only four stars outside the cluster itself could be said to lie along the tails. This is probably not surprising, however, given that Pal 5 has very few blue HB stars; most of the points in Figure 3 are likely to be foreground contaminants.

Assuming that tidal streams closely parallel the orbits of their parent clusters (Odenkirchen et al. 2003), we can use the observed orientation of the extended stream to better constrain the current velocity and global orbit of Pal 5. Using the analytic Galactic model of Allen & Santillan (1991) (which includes a disk as well as a spherical bulge and halo), we integrate along the orbit of Pal 5 both forwards and backwards and project this path onto the sky. We adopt $R_\odot = 8.5$ kpc and $v_c = 220$ km s $^{-1}$, and use Odenkirchen et al. (2002)’s heliocentric radial velocity measurement for Pal 5 of -58.7 ± 0.2 km s $^{-1}$.

Using Cudworth’s 1998 (unpublished, but listed in Dinescu, Girard, & van Altena (1999)) proper motion measurement of $\mu_\alpha \cos(\delta), \mu_\delta = (-2.55 \pm 0.17, -1.93 \pm 0.17)$ mas yr $^{-1}$, we arrive at an expected orbit projection as shown by the solid line in Figure 3. Other proper motion measurements for Pal 5 (e.g. Schweizer, Cudworth, & Majewski (1993); Scholz et al. (1998)) result in orbit projections which are almost perpendicular to the stream in Figure 3. With due allowance for our incomplete knowledge of the Galactic potential and for the limitations of Allen & Santillan (1991)’s model, the projected orbits implied by the existing proper motion measurements do not agree particularly well with the orientation of Pal 5’s tidal tails.

Based on the width of the “S” curvature of the tails in the immediate vicinity of Pal

5, we adopt a mean offset between Pal 5’s projected orbit and the centerlines of the tails of 0.2° . We then define a set of normal points which trace the highest surface densities along the tails in Figure 2. Finally, we project orbits for a grid of possible proper motions and use χ^2 minimization to obtain a “best fit”. The minimum χ^2 solution is shown by the dotted line in Figure 3.

Over the length of the stream for which we have good signal to noise ratio, our best fit orbit parallels the stream contours quite well. Departures appear to be of high order rather than systematic, indicating that a spherical halo potential is adequate to fit the data. There is a suggestion that the southern tail and the model may be parting company near the limits of the field, and it will be interesting to see whether the simple potential used here can be made to fit the continuation of the southern tail when additional data become available.

The proper motion which corresponds to our best fit orbit has $\mu_\alpha \cos(\delta), \mu_\delta = (-2.27 \pm 0.08, -2.19 \pm 0.03)$ mas yr $^{-1}$, where the uncertainties correspond to the 99% confidence interval. We note that, while the uncertainties are influenced by measurement errors, random motions of stream stars, confusion with the foreground population, variable extinction across the stream, they do not incorporate uncertainties in our adopted model for the Galaxy. Our modeled proper motions are within $\sim 1.7\sigma$ of Cudworth’s measured values. For the orbit shown in Figure 3, the corresponding space velocities of Pal 5 are $U, V, W = (48.3 \pm 2.0, -334 \pm 5, -14.2 \pm 2.1)$ km s $^{-1}$. The (radial) period of the orbit is 2.9×10^8 yrs, with peri and apogalacticon of 7.9 and 18.8 kpc, respectively. These values agree very well with similar estimates by Odenkirchen et al. (2003) based on their less extensive data set.

The best fit orbit predicts a total length of $\simeq 8.3$ kpc for the northern arm. The width of the tail appears roughly constant along its length, though the signal to noise ratio is low enough that we cannot rule out a possible widening of the tail beyond R.A. = 241.6. Comparing the contours in Figure 3 with the best fit orbit, there is also a suggestion of “wobbling” of the stream eastwards of R.A. = 239°, and perhaps a 0.5° northward jog of the tail at $241.5^\circ < \text{R.A.} < 244.5$. If borne out by future kinematic data, this could be evidence for irregularities in the Galactic potential or for a weak encounter between stream stars and a substantial mass concentration (e.g. a large molecular cloud) during a recent passage through the disk. A more extensive analysis of the stream and its consequences will be presented in a forthcoming paper.

4. Conclusions

Applying optimal contrast filtering techniques to SDSS DR4 data, we have detected a continuation of Pal 5’s trailing tidal stream out to almost 19° from the cluster. Combining this with the already known southern tail of Pal 5 yields a stream some 22.5° long on the sky. The extension of the stream shows marked fluctuations in surface density along its length which are presumably a natural consequence of the episodic nature of tidal stripping. The orientation of the stream is in accord (at the 1.7σ level) with one of the existing measurements of Pal 5’s proper motion. The stream can be modeled reasonably well using a model Galactic potential with a spherical halo, and we are able to place much better constraints on the current space motion of the cluster.

We can use the current data set to assign to each star a probability that it is associated with Pal 5’s tidal stream. These probabilities can be taken to the telescope, where we will need to measure radial velocities sufficiently accurately to unambiguously tie the stars to the stream. Ultimately, the vetted stream stars will become prime targets for the Space Interferometry Mission, whose proper motion measurements will enable very much stronger constraints to be placed on both the orbit of the cluster and on the potential field of the Galaxy.

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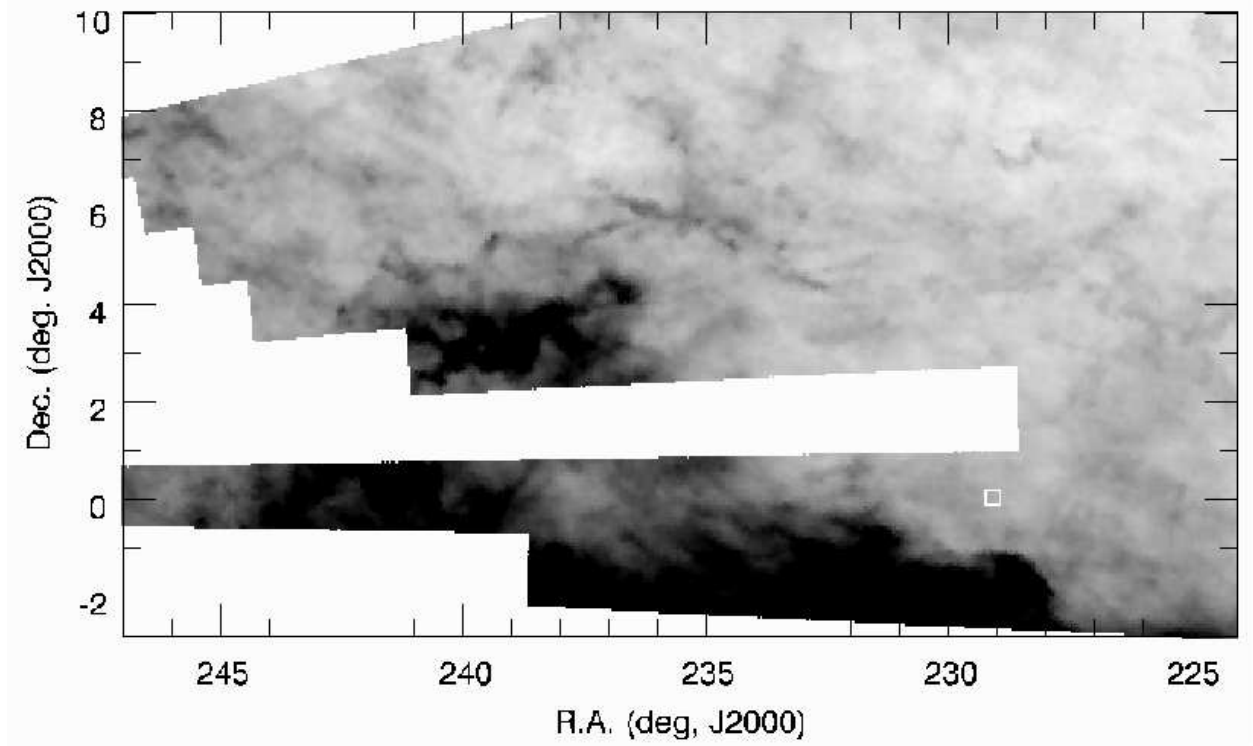


Fig. 1.— Distribution of $E(B-V)$ over the DR4 field surrounding Pal 5. The position of Pal 5 is indicated by the open square at R.A., dec = (229,-0.11). The color excess ranges from 0.02 along the northern border of the image, to 0.3 along the southern edge.

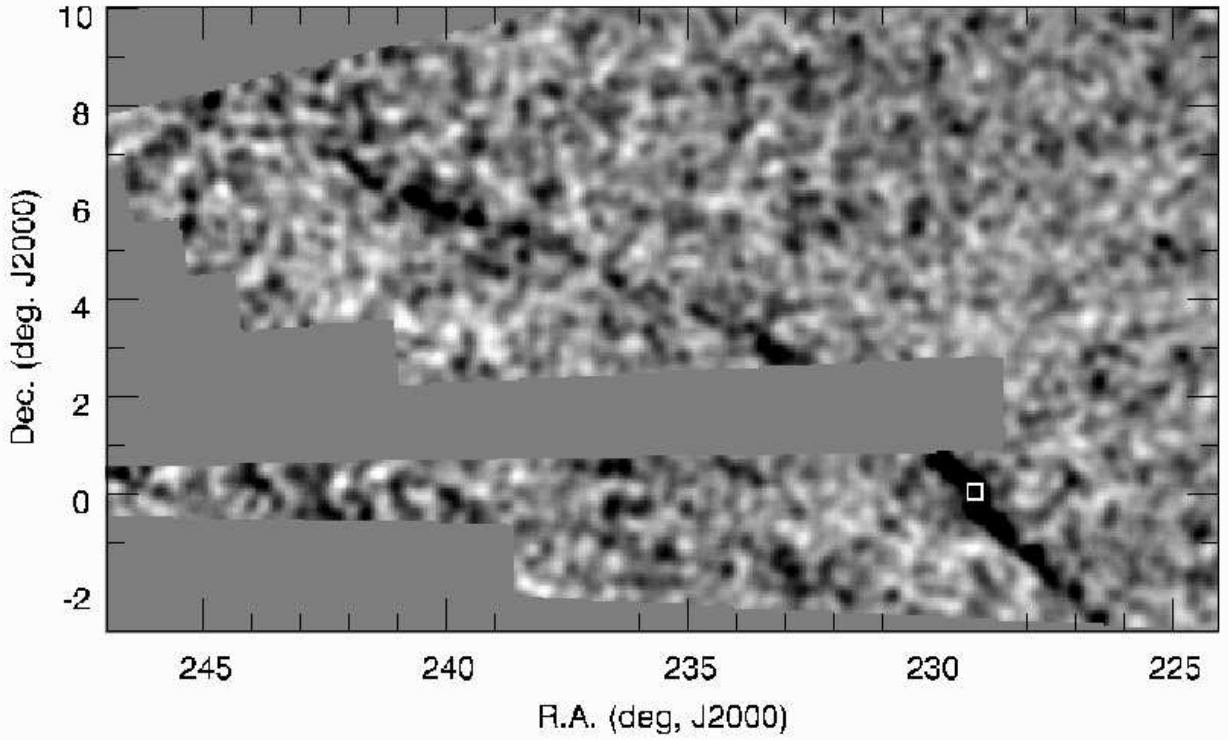


Fig. 2.— Smoothed, summed weight image of the SDSS field after subtraction of a low-order surface fit. Darker areas indicate higher surface densities. The location of Pal 5 is indicated by the open square at R.A., dec = (229,-0.11). The weight image has been smoothed with a Gaussian kernel of width of 0.15° . The irregular borders and the missing stripe are defined by the limits of SDSS Data Release 4. The newly discovered extension of Pal 5’s tidal stream extends from R.A., dec = $(234^\circ, 3.2^\circ)$ to $(246^\circ, 7.9^\circ)$.

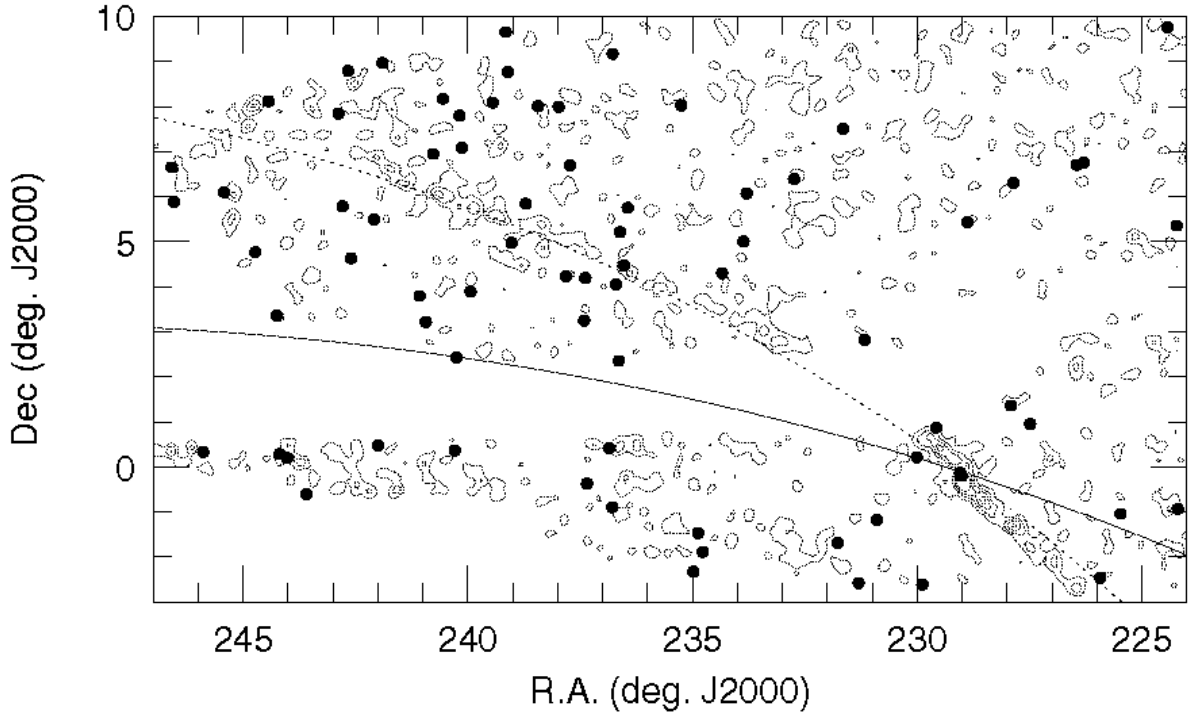


Fig. 3.— Surface density contours and the orbit of Pal 5. Contours are taken from the weight image in Figure 2 and represent the 2, 3, 4, and 5 σ levels. The filled circles show the positions of candidate blue horizontal branch stars. The solid line shows an orbit integration based on the Cudworth’s 1998 measurement of the cluster’s proper motion (Dinescu, Girard, & van Altena 1999). The dotted line shows an orbit with $\mu_\alpha \cos(\delta), \mu_\delta = (-2.27, -2.19)$ mas yr $^{-1}$.